A magnetic regenerator

S. W. Oh and W. B. Powell
Department of Physics,
University of Birmingham,
Birmingham 15

Presented by S. W. Oh

ABSTRACT

It is common to use regenerators to extract beams from synchrocyclotrons; but their use in AVF cyclotrons is rare. The reasons for this may be partly historical and theoretical; but there are also technical difficulties connected with the narrower gaps in AVF cyclotrons and the need to vary the regenerator strength.

A regenerator has been in use on the 40 in radial ridge cyclotron for the past six years. This was initially designed as an electrostatic element, and although it worked (at times very well), over the years it became the most unreliable component in the machine. This was due to occasional but serious breakdown of the 40 to 50 kV positive voltage electrode which no amount of redesign was successful in eliminating. To overcome this difficulty a magnetic regenerator was constructed. This consists of two small, specially shaped, soft iron components. When operated with an electrostatic regenerator with a small voltage of either polarity, the extraction efficiency and beam quality were found to be satisfactory and the regenerator system was both adjustable in strength and completely reliable.

1. INTRODUCTION

Extraction of the accelerated beam from the Birmingham Radial Ridge Cyclotron[1] is achieved with the aid of a regenerative system.[2]

As shown in Fig. 1, the system consists of a regenerator which gives an inward deflection and a peeler which gives an outward deflection to the beam each time it passes through them. Originally the regenerator (see Fig. 2) was wholly electrostatic (39 kV for the 12 MeV deuteron beam and 50 kV for the 32 MeV ^{3}He beam). A serious problem with this system has been the electric breakdown of the positive voltage electrode of the electrostatic regenerator (e.s.r.) due to the self breeding mechanism of the trapped electrons around the electrode. In spite of early favourable results,[3] in routine operation the regenerator condition frequently deteriorated and since no reliable cure to this problem could be found it was decided to introduce a magnetic regenerator by the side of the existing e.s.r. The magnetic regenerator would provide the main deflecting force and the

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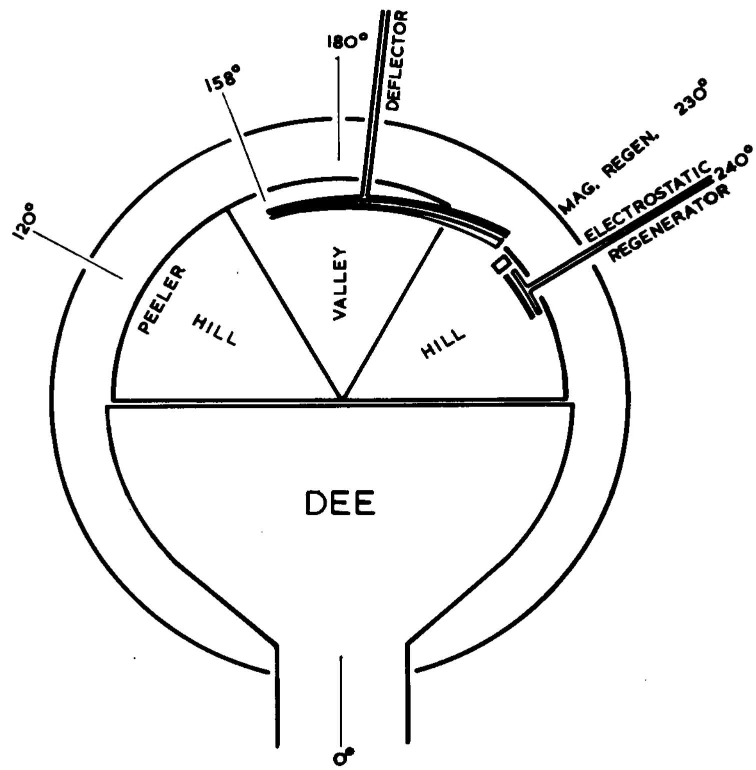

Fig. 1. Schematic view of cyclotron, showing positions of the electrostatic regenerator with the new magnetic regenerator beside it

e.s.r., operating at low—and possibly negative—voltage, would provide some control of strength and shape of the field.

Unlike the e.s.r., the magnetic regenerator disturbs the cyclotron field itself and therefore the design presents a number of extra problems. These are usually solved with a model, or the actual magnet, using a series of trial shapes each followed by measurements of the field; but this was not possible in the present case because no model existed and the cyclotron could not be opened up for a measurement programme. An alternative would be to do theoretical calculations with the aid of a large capacity computer; but this seemed to be a formidable task and so a simplified procedure was adopted.

In proceeding to the design, the following conditions were made:

(a) The beam orbit must be nearly straight over the region of the field produced by the magnetic regenerator (in fact the azimuthal extent is about 10°).

(b) The regenerator body (ARMCO iron alloy) must be magnetically saturated when placed in position; (the cyclotron field at the position of the regenerator is of the order of 20 kG).

(c) The magnetisation $\bar{M}$ of the regenerator body must be nearly uniform and vertical; (the uniformity of $\bar{M}$ depends on the geometrical shape of the body, and thus, for example, elliptical cross-sections are preferable).

(d) As the gap between the pole tips of the cyclotron magnet is small (actually 7·5 cm) the presence of the magnetic regenerator disturbs the cyclotron field itself. It is helpful to have the vertical extent of the regenerator small compared with the gap so that the distortion in the cyclotron field can be reasonably approximated by the first one or two pairs of images.

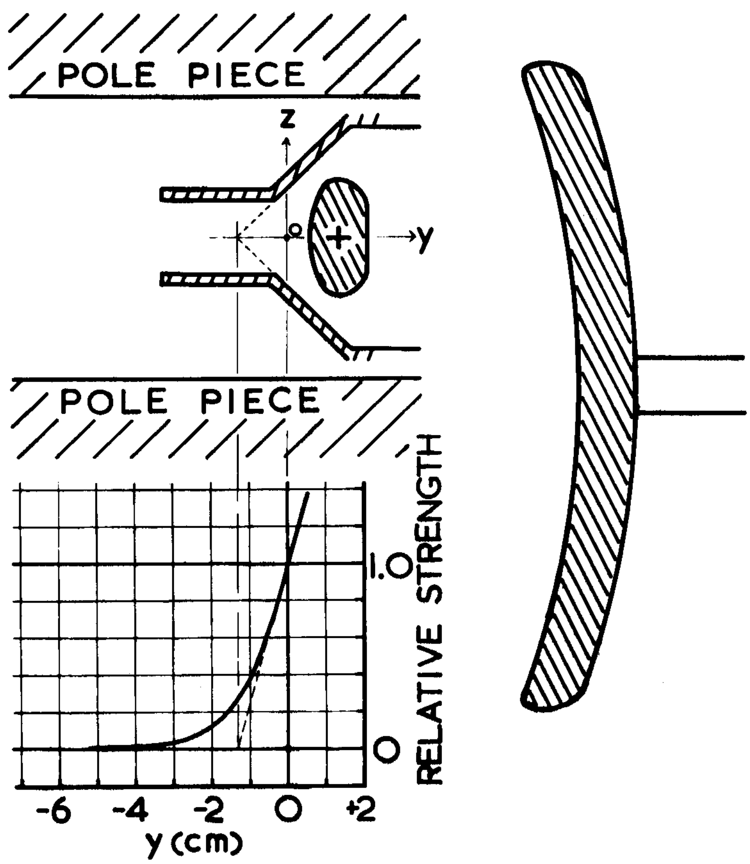

Fig. 2. Schematic view of electrostatic regenerator (in plan and elevation). In normal operation the electrode operates at positive and the surroundings at earth potential. The equipotential lines approximate to a hyperbola. The relative strength of the regenerator as a function of y *(radial direction) is also shown. Extraction occurs at* y = 0

Take the x-axis along the beam path, the y-axis along the radius of the cyclotron and the z-axis along the (vertical) magnetic field of the cyclotron. Then the regenerator magnetic field outside the regenerator body is:

$$\bar{B}(x, y, z) = \nabla \frac{\mu_0}{4\pi} \int \bar{M}(x', y', z') \nabla \left(\frac{1}{r}\right) \mathrm{d}v' \tag{1}$$

where $r = \sqrt{(x - x')^2 + (y - y')^2 + (z - z')^2}$, and $\mathrm{d}v' = \mathrm{d}x' \, \mathrm{d}y' \, \mathrm{d}z'$ is the volume element of the regenerator body. Therefore:

$$\bar{B}_z = \frac{\mu_0}{4\pi}\frac{\partial}{\partial z}\int \bar{M}(x',y',z')\,\nabla\left(\frac{1}{\sqrt{(x-x')^2+(y-y')^2+(z-z')^2}}\right)\,dx'\,dy'\,dz' \qquad (2)$$

From assumption (a) the deflection angle θ of the beam due to the regenerator is:

$$\begin{aligned}\theta &= -\frac{\Delta v_y}{v} = \frac{1}{v}\int\frac{e}{m}\,v\,B_z\,dt = \frac{e}{mv}\int B_z\,dx \\ &= \frac{e}{mv}\frac{\partial}{\partial z}\frac{\mu_0}{4\pi}\int\left[\bar{M}(x',y',z')\,dx'\,dy'\,dz'\int dx\,\nabla\left(\frac{1}{\sqrt{(x-x')^2+(y-y')^2+(z-z')^2}}\right)\right] \\ &= \frac{e}{mv}\frac{\partial}{\partial z}\left\{\frac{\mu_0}{2\pi}\int\left[\int(\bar{j}My+\bar{k}Mz)\,dz'\right]\times\right. \\ &\qquad\left(\bar{j}\frac{\partial}{\partial y}+\bar{k}\frac{\partial}{\partial z}\right)\ln\sqrt{(y-y')^2+(z-z')^2}\,dy'\,dz' \end{aligned} \qquad (3)$$

The bracketed term in the above expression is identical in form to the two dimensional magnetic field:

$$\bar{B}'(y,z) = \frac{\partial}{\partial z}\frac{\mu_0}{2\pi}\int \bar{M}'(y',z')\nabla\left[\ln\sqrt{(y-y')^2+(z-z')^2}\right]dy'\,dz' \qquad (4)$$

with the hypothetical two dimensional magnetic dipole distribution over the regenerator body given by:

$$\bar{M}'(y',z') = \int\left[\bar{j}My(x',y',z')+\bar{k}Mz(x',y',z')\right]dx' \qquad (5)$$

Therefore θ can be calculated through the two dimensional field, Eqn (4), once the two dimensional dipole distribution, Eqn (5), is known. For simple geometries of the regenerator shape, assumptions (b) and (c) usually lead to analytical expressions for $\bar{B}'(y,z)$ and $\bar{M}'(y',z')$. Fields produced by images will be obtained by displacing y and z in Eqn (4) by appropriate amounts.

2. REGENERATOR DESIGN AND PERFORMANCE

As a preliminary test, a trial magnetic regenerator, Fig. 3, was constructed. This consisted of a pair of iron cylinders with 2d = 29 mm mutual distance, each having radius $\alpha = 6{\cdot}3$ mm and length $l = 20$ mm. With this geometry the magnetisation should be nearly uniform and oriented along the cyclotron field. The regenerator was placed at $\phi = 230°$ (10° before the e.s.r., see Fig. 1.) where the cyclotron magnetic field is $B_{ex} = 1{\cdot}9\ T$ (19 kG). The magnetic field, Eqn (4), for the above geometry becomes:

$$B_z'(y,z) = l\,B_{ex}\frac{\mu_r-2}{\mu_r+1}\left\{\frac{\left(\frac{d-z}{a}\right)^2-\left(\frac{y}{a}\right)^2}{\left[\left(\frac{d-z}{a}\right)^2+\left(\frac{y}{a}\right)^2\right]^2}+\frac{\left(\frac{d+z}{a}\right)^2-\left(\frac{y}{a}\right)^2}{\left[\left(\frac{d+z}{a}\right)^2+\left(\frac{y}{a}\right)^2\right]^2}\right\} \qquad (6)$$

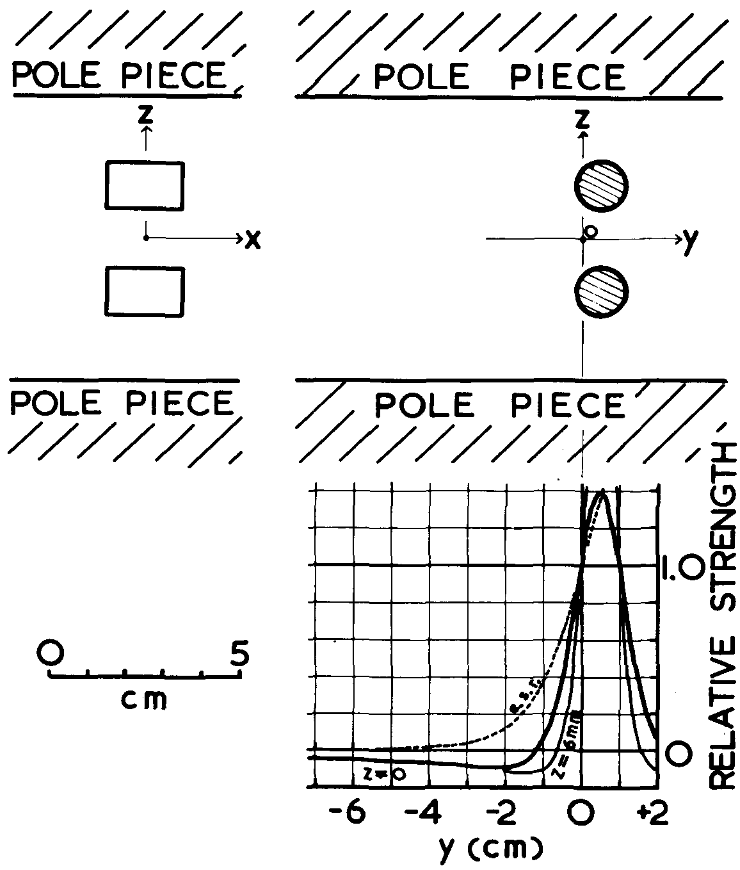

Fig. 3. Trial magnetic regenerator consisting of a pair of iron cylinders. The relative strength of the regenerator as a function of y *is shown at* z = *0 and also at* z = *6 mm, the strength of the electrostatic regenerator (e.s.r.) is also shown for comparison. There are considerable differences between the shapes of the curves. Extraction occurs at* y = *0*

The above field, after making a correction for the image effect, is also shown in Fig. 3. As can be seen from the figure, the regenerator characteristic is far from independent of beam height and therefore the beam quality and extraction efficiency can be expected to be poor (in the 'ideal' linear regenerator the deflecting force increases linearly with radius and is independent of vertical position). It can be seen by comparing with Fig. 2 that the characteristics of the magnetic regenerator differ from the e.s.r. mainly in the region of the tail where the beam spends much of its time.

Subsequent extraction of the deuteron beam with the magnetic regenerator showed that the required voltage for the e.s.r. was halved (about 18 kV) as had been estimated. Electric breakdown was much less troublesome; but the extracted beam line had shifted considerably and the beam shape at the exit port was poor. An extraction efficiency of 30–40% was observed as opposed to 60–70% with the e.s.r. alone. At the same time the first harmonic coils of the cyclotron were only just strong enough to compensate for the tail field of the magnetic regenerator.

The performance of the trial magnetic regenerator had shown that the principles of the design method were sound, and it now remained to refine the design, particularly in the region of the tail.

A series of progressively more complicated shapes were tried finishing with the final magnetic regenerator described below. The main differences between the final and the trial regenerators are that the shape of the $B_z'(y, z)$ field, although generally steeper, now more nearly resembles that of the e.s.r. (in particular the tail region is shallower and wider in extent to reduce the compensation required from the first harmonic coils), and the z dependence of the $B_z'(y, z)$ field is minimised to improve the beam quality and extraction

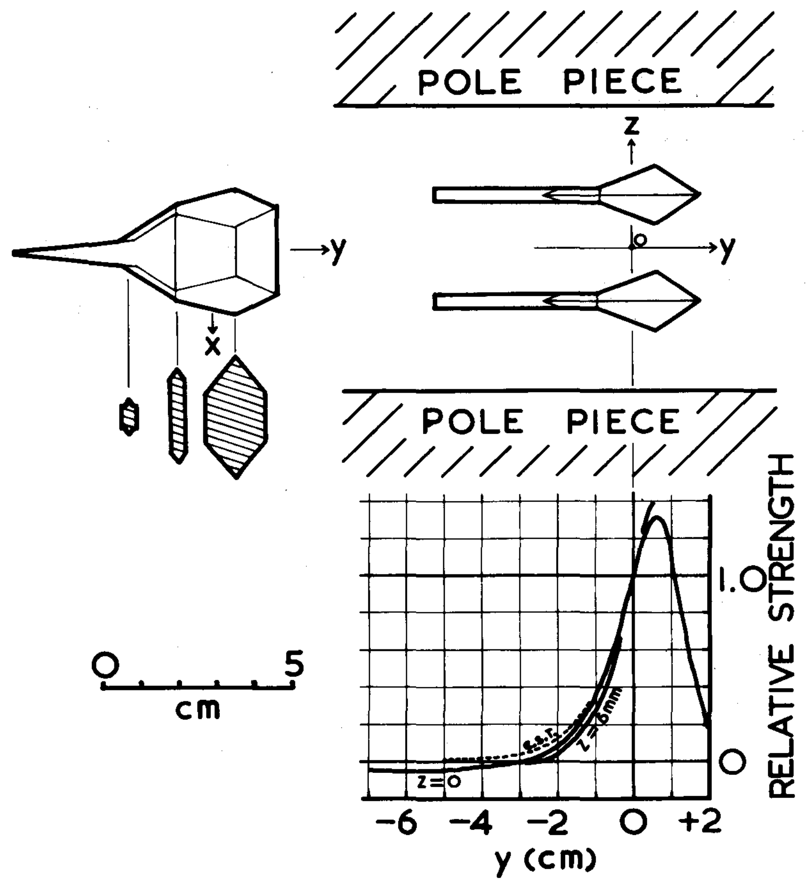

Fig. 4. Final magnetic regenerator (in plan, elevation and section). The relative strength of the regenerator as a function of y *is shown at* z = 0 *and* z = 6 *mm; the strength of the e.s.r. is also shown for comparison. The three curves now have nearly the same shape over the critical region. Extraction occurs at* y = 0

efficiency. A sketch of the final regenerator is given in Fig. 4 where the estimated field for $B_z'(y, z)$, after correction for the image effect of the cyclotron pole tips, is also shown. The required voltage for the auxiliary e.s.r. is about −16 kV compared with +39 kV with the e.s.r. alone and, because of the change in polarity of the voltage, the breakdown problem has been eliminated. An extraction efficiency of 50% was achieved after a slight re-alignment of the septum, and the energy resolution is unaltered (~0·4% or better). The beam shape at the exit port is also unchanged.

3. CONCLUSION

It will be noticed that the present magnetic regenerator is stronger than it need be; it has not been changed because there is little incentive to do so. However, if a similar regenerator were to be designed for a variable energy cyclotron it would seem to be best to choose its strength so that the auxiliary e.s.r. could be operated by equal amounts on either side of zero voltage. It will also be noticed that the gap between pole tips is smaller than is the case for most AVF cyclotrons; with larger gaps there would be less interference with the main cyclotron field and the regenerator should be correspondingly easier to design.

In general the performance of the magnetic regenerator (in combination with the existing e.s.r.), which has been in use since 1967, is as good as the previous electrostatic regenerator. It has the advantage of using very little space and, when used in conjunction with a weak electrostatic regenerator, can be varied in strength without introducing any voltage holding problems. While magnetic measurements would be desirable, the design technique outlined above has shown that it is possible to construct a variable strength regenerator and yet manage without them.

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